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Observation of mass loading in the Io plasma torus

Michael E. Brown

Department of Astronomy, University of California at Berkeley

Abstract. Ground-based high-resolution spectra of emission from the Io plasma torus obtained during 53 nights of observation over a seven month period are used to measure the torus rotation speed and discern regions of the torus that are slowed by mass loading of newly ionized materials. The amount of torus slowing implies that between 2000 and 3000 kg sec^{-1} are being ionized by the torus. The slowing is spread azimuthally throughout the orbit of Io, suggesting that neutral materials emanating from Io are distributed around Jupiter much more uniformly than currently believed.

Introduction

Although the plasma torus surrounding Jupiter and Io has been observed extensively, we still lack a basic understanding of the interactions between the torus and the presumed sources of the torus – Io, the Io atmosphere, and the neutral clouds near Io's orbit. A major difficulty in understanding the interactions is that the Io atmosphere and the major components of the Io neutral clouds are difficult to observe. Observations have only recently begun to directly explore the nature of the Io atmosphere [Lellouch et al., 1992]. The sodium neutral cloud emanating from Io has been observed for 20 years, but sodium is only a trace constituent observable because of its large cross section for resonant scattering of sunlight. The dominant oxygen and sulfur neutral components are difficult to detect [Ballester et al., 1987], and the shape and size of possible oxygen and sulfur clouds are unknown.

Though the properties of the Io atmosphere and major neutral clouds are poorly known, their interactions with the torus can be seen by measuring the torus rotation speed: to first order, the torus ions are locked to the rotation of the Jovian magnetic field (at the "corotation speed"), but the ions are slowed wherever neutral materials (presumably from Io's atmosphere or neutral clouds) are ionized and accelerated by the magnetic fields to the corotation speed [Pontius and Hill, 1982]. These slow-downs show the location and amount of the fresh ionization in the torus.

Velocities around 5% lower than the corotation speed were measured by the Voyager Plasma Science instrument [Bagenal, 1985], and over the course of 7 nights by high-resolution ground-based spectroscopy [Brown, 1983]. These observations showed that the velocities were variable, but spatial and temporal coverage were too sparse to allow an understanding of the characteristics and causes of the variabilities. A recent campaign of intensive monitoring of the torus using the coudé auxiliary telescope (CAT) at Lick Observatory was undertaken in order to completely map the torus interactions. Full spatial coverage was obtained through the use of a very long spectral slit which simultaneously captures light from the entire length of the torus, while observations for 53 nights over a seven month period provided extensive temporal coverage.

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Observations

Observations of the Io plasma torus were obtained using the 0.6 meter CAT feeding the Hamilton echelle spectrograph at Lick Observatory. A total of 222 high quality spectra spanning 53 nights of observation from 2 December 1991 until 1 June 1992 were used for this analysis. Each is a high-resolution ($\lambda/\Delta\lambda \sim 40000$) very long slit (slit length $\sim$ 6 arcminutes) spectrum covering the torus [SII] 6717, 6731 Å emission doublet. For each 40 minute CCD integration the spectral slit was aligned parallel to the predicted position of the Jovian centrifugal equator at the midpoint of the exposure (assuming a tilted-dipole and centrifugal equator 2/3 of the way from the spin equator to the magnetic equator) and centered on Jupiter. Emission from Jupiter was attenuated by covering the center of the slit with strong neutral density filter. A typical spectrum is shown in Figure 1. Emission from the two torus lines is slanted by the doppler shift caused by the torus rotation; reflected solar continuum from Jupiter appears as a vertical band of emission in the center of the spectrum. Though the torus emission appears to extend from 0 to about 5.5 R_J, the emission actually all originates beyond about 5.0 R_J [Trauger, 1984]; all emission appearing interior to this distance is the projected view of the torus in front or behind Jupiter.

All of the spectra were reduced identically. First, each CCD frame was bias-subtracted, flat-fielded, and corrected for residual curvature along the spatial and dispersion axes. The amount of Jovian scattered light (visible in Figure 1 as continuum emission extending past the radius of Jupiter) was determined from the spatial profile in spectral regions far from the torus emission. For a typical spectrum, the scattered light had an intensity equal to about 30% of the torus emission at 5 R_J and about 50% at 6 R_J. The scattered light was removed by subtracting a synthetic spectrum consisting of a Jovian spectrum having the scattered light spatial profile. The torus rotation velocity was measured from these corrected, continuum-subtracted spectra by fitting a gaussian profile to each emission profile and

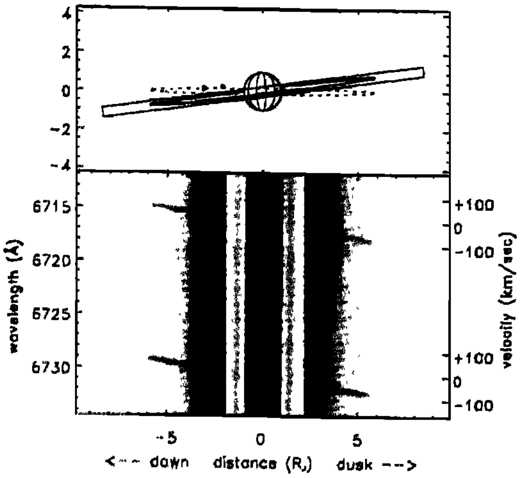

Figure 1. A long slit spectrum of the Io plasma torus from the night of 3 April 1992. The upper panel shows the geometry of the Jovian system at the time of the observation with the dashed line indicating the orbit of Io, and the solid line circling Jupiter tracing the path of the torus. The rectangle shows the projected size and orientation of the spectral slit. The bottom panel shows the spectrum. The two slanted lines are [SII] 6717, 6731 Å emissions from the torus.

determining the central emission wavelength of the line at each spatial position of the spectrum. The deviation of the torus from corotation velocity was then determined by subtracting the corotation velocity at each distance from the velocity measured (for a Jovian rotation period of 9.925 hours, the corotation velocity is 12.56 km s^{-1} $R_J{}^{-1}$, or 74.2 km s^{-1} at Io's orbital radius). For complete details on the observations and reductions, see Brown [1994].

Results

To examine the average velocity behavior of the Io plasma torus, the velocities were measured from a sum of all 222 spectra. Figure 2 shows the deviation from the corotation velocity measured from this sum. The error bars in the figure represent one sigma errors in the gaussian curve fitting procedure determined from a large Monte Carlo simulation of synthetic data with varying widths and noise levels. The distribution of torus longitudes in the spectra is essentially random, so the sum contains equal numbers of individual spectra of differing geometric configurations. The effect of this non-uniformity in the spectra is explored in Brown [1994], where it is shown that beyond 5 R_J the effects on the measured velocity are smaller than the error bars shown in Figure 2, permitting these effects to be ignored in the analysis below. The velocities have been centered relative to a wavelength of 6730.89Å, which is a shift of 0.04Å or 1.8 km s^{-1} from the predicted laboratory value of 6730.847±0.023 Å [Kaufman and Sugar, 1986]. This velocity shift is close to the 2 km s^{-1} shift predicted by the action of the dawn-dusk electric field [Barbosa and Kivelson, 1983], but because of the uncertainties in the laboratory wavelength and in the absolute wavelength calibration of the spectra at this level of accuracy, the significance of this shift is unclear.

The velocity measurements show that outside of approximately 5 R_J the torus rotates more slowly than the corotation velocity. The amount of mass loading in the torus that would cause the measured deviations from corotation can be determined from a modification of the equations of Pontius and Hill [1982]. They considered constant mass loading in an axially symmetric annulus in the torus. A generalization to allow radial variations in the mass loading yields an expression for the mass loaded per unit time in a differential annulus as a function of the annulus L-shell:

$$\dot{\mu}(L)\mathrm{d}L = (4\pi R_J B_J^2 \Sigma)\frac{\sqrt{1-L^{-1}}}{L^5 v_{co}(L)}\,\delta v(L)\mathrm{d}L, \quad (1)$$

where R_J is the radius of Jupiter, B_J is the surface equatorial magnetic field of Jupiter, $v_{co}(L)$ is the difference between the orbital and corotation speeds at radius L, δv is the measured corotation lag, and Σ is the height-integrated Pederson conductivity of the Jovian ionosphere. Theoretical estimates yield values for the Pederson conductivity of between $\Sigma \sim 0.2$ mho, for regions where the ionization is dominated by solar EUV radiation, to $\Sigma \sim 10$ mho for regions where intense particle precipitation is present [Strobel and Atreya, 1983]. The amount of mass loading calculated below is normalized to a value of $\Sigma = 1$ mho.

Use of the equation above for mass loading still assumes that mass loading is axially symmetric. A full treatment allowing radial and angular variations in the mass loading has yet to be accomplished. Figure 2 clearly shows that axial symmetry does not exist; the equation will still be used in the sense that total mass loading will be calculated separately for the dawn and the dusk sides assuming axial symmetry; the true total mass loading then lies between the two calculated numbers. Use of the equation also assumes that δv is the true corotation deviation at radius L, rather than the integrated line-of-sight velocity observed. A careful geometric deprojection will be needed in order to accurately map the precise locations of the torus interactions, but because of the fast decrease in torus intensity with radius, the line-of-sight velocity is a good initial estimate of of the true velocity, particularly beyond about 5.5 R_J. Work on deprojection is presently underway.

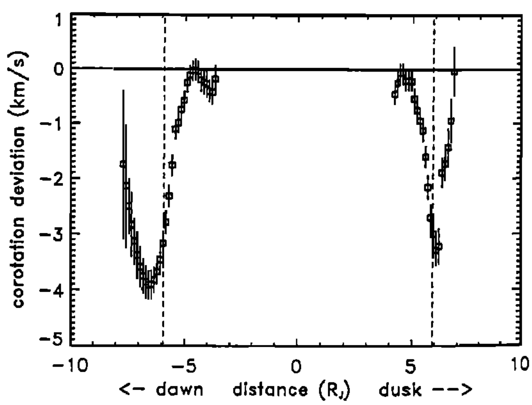

Figure 2. The average deviation from the corotation velocity of the Io plasma torus measured from a sum of 222 spectra. A strictly corotating torus would fall along the horizontal line at zero velocity.

Figure 3 shows the mass loading determined from the equation above. This figure shows that on both sides of Jupiter the mass loading peaks very close to the radius of Io's orbit, a clear indication that mass loading of material from Io, and not some other mechanism, is indeed the major cause of the velocity deviations. The total mass loading in the torus is determined by integrating under the curves in the figure. On the dawn side the total is 3050±400 kg $s^{-1} \times (\Sigma/$ 1 mho), while on the dusk side the total is 2000±300 kg $s^{-1} \times (\Sigma/$ 1 mho) (again, because the corotation deviations are not axially symmetric, the true total mass loading is probably between about 2 and 3 $\times 10^4$ kg $s^{-1} \times (\Sigma/$ 1 mho)).

To examine how the mass loading varies around Io's orbit the spectra were binned into twelve groups based on the Io phase angle, γ, at the time of the observation ($\gamma = 0$ when Io is directly behind Jupiter, and $\gamma = 90$ and 270 degrees at dawn and dusk elongation, respectively), and the velocities were measured for the sum of the spectra in each bin. Each bin contains an average of 18 individual spectra distributed randomly over torus longitudes, so a single bin will contain spectra with the torus in both open and closed configurations. The distribution of torus configurations also means that within a single bin, Io can be a variety of distances from the torus, although at one phase angle. For example, at a phase of $\gamma = 90$ with the torus in a closed configuration, Io is about 0.7 R_J from the torus centrifugal equator, while at the same phase but with the torus in an open configuration, Io lies right on the centrifugal equator. Because all bins contain about the same number of spectra of each configuration, the velocities measured for each can be directly compared. The only exception to this general rule occurs because torus observations are locally contaminated wherever Io falls directly on the slit. This contamination prevents any measurements within a few arc-seconds of Io, so direct interactions of the satellite and the torus are not seen. The neutral clouds extending from Io are much larger, so the contamination by Io does not effect observations of interactions with them. Currently scheduled *HST* observations will soon be used to fill in this gap.

Figure 4 shows the line-of-sight corotation deviation as a function of radius on the dawn and dusk sides for

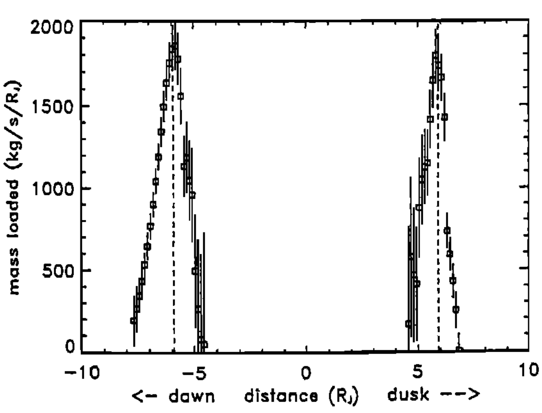

Figure 3. The total mass loading in the Io plasma torus calculated from the measured corotation deviations.

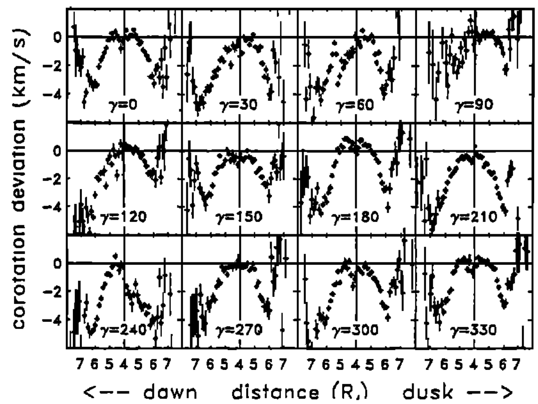

Figure 4. The corotation deviation as a function of Io phase angle (γ).

each Io phase. Because the continuum emission from Jupiter is quite broad and flat, the center of Jupiter cannot be determined to better than about a 0.1 R_J accuracy in these observations. The corotation velocity varies by more than 1 km s^{-1} over this distance, so the center of each summed spectrum had to be artificially shifted by an rms average of 0.5 km s^{-1} (shifting the center of a spectrum has the effect of moving the deviation velocities up on one side of Jupiter and down on the other). The amount of shift was determined using the physically plausible criteria that no velocities should appear higher than corotation and that whenever possible the resulting velocity spectra should look like the average velocity spectrum shown in Figure 2. For most of the spectra the amount of offset was easily determined, as the velocity spectra in Figure 4 attest. The $\gamma = 240$ spectrum presented the most difficulty in shifting. The dawn side of that spectrum appears much like the other dawn spectra, but the dusk side is different from all others. The final offset was obtained by simply fitting the dawn side and making the dusk side follow.

Figure 5 plots the integrated mass loaded as a function of Io phase angle for both the dawn and dusk sides. On both sides of Jupiter, the torus slow-downs are widely spread over the orbital phase of Io. On the dusk side the calculated mass loading is enhanced when Io is near dusk elongation and is weakest when Io is 180 degrees away at dawn elongation. On the dawn side no variation is visible in the mass loading.

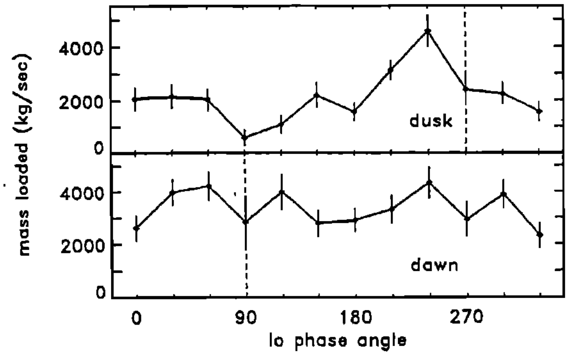

Figure 5. The total mass loaded as a function of Io phase for the dawn and dusk sides.

Discussion

These observations have shown that the torus mass loading, and thus the torus-Io interaction, is strongest at Io's orbital radius and spread almost uniformly around Jupiter. The large angular spread is surprising in view of recent modeling [Smyth and Marconi, 1993] which suggests that, even though the neutral clouds of oxygen and sulfur should be larger than those of sodium owing to the longer lifetimes against ionization of sulfur and oxygen, mass loading in the torus should still be confined closer to Io where the total neutral density is highest.

A uniform mass loading does not necessarily imply a uniform distribution of neutrals around Jupiter: the amount of mass loading is determined by the neutral material density, the electron density and temperature (for electron impact ionization) and the ion density and temperature (for charge-exchange ionization). Obtaining a relatively uniform distribution of mass loading around Jupiter requires either than each of these individual parameters is uniform or that some feedback makes the total effect uniform in spite of individual changes. The most likely conclusion seems to be that the distribution of neutrals around Jupiter is indeed more uniform than currently believed.

The total mass loading calculated is in good agreement with previous estimates of mass loading and energy input in the torus. Hill [1980] used the Voyager observations of centrifugal slipping in the dusk-side outer Jovian magnetosphere to calculate a total mass loading rate of 1700 $\times(\Sigma/\ 1\ \text{mho})$ kg s^{-1} (this measurement depends on Σ in the same manner), similar to the total measured here. Based on Voyager measurements of the radiative output of the torus, the total power emitted by the torus is between 3 and 6×10^{12} W [Shemansky 1987]. Of this total power, from 30 to 75% – or between 1 and 4.5×10^{12} W – is thought to be provided by the acceleration of newly ionized materials [Shemansky, 1988]. The total power input by mass loading is easily calculated as the kinetic energy gained by newly ionized particles as they are accelerated from orbital to almost corotation speed. For the amount of mass loading measured above, the total power input to the torus is between 3 and $5\times10^{12} \times (\Sigma/1\ \text{mho})$ W. For $\Sigma \lesssim 1$ mho the power input from the mass loading measured is consistent with the power output measured in the torus.

These results have provided a first look at the radial and angular structure of the sources of the Io plasma torus. Further analysis of these data, including a careful geometric deprojection to remove the effects of the integrated line-of-sight measurements, is underway in an attempt to refine the mass loading estimates and to investigate the dawn-dusk asymmetries and understand the consequences of an electric field in the system. In addition, the extensive time coverage of these observations over a six month period will allow the time variability of the mass loading to be studied and will add greatly to the understanding of the physical processes in the Io plasma torus.

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M. E. Brown, Dept. of Astronomy, University of California, Berkeley, CA 94720 (e-mail: brown@bigz.berkeley.edu)

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